Foundation of Cryptography (0368-4162-01), Lecture 6

More on Zero Knowledge

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Part I

Non-Interactive Zero Knowledge

Interaction is crucial for ZK

Claim 1

Assume that $\mathcal{L} \subseteq \{0,1\}^*$ has a one-message ZK proof (even computational), with standard completeness and soundness,[a] then $\mathcal{L} \in \mathrm{BPP}$.

[a] That is, the completeness is $\frac{2}{3}$ and soundness error is $\frac{1}{3}$.

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    1. Witness Indistinguishability $\{\langle(\mathsf{P}(w_x^1), \mathsf{V}^*)(x)\rangle\}_{x\in\mathcal{L}} \approx_c \{\langle(\mathsf{P}(w_x^2), \mathsf{V}^*)(x)\rangle\}_{x\in\mathcal{L}}$, for any $\{w_x^1 \colon (x, w_x) \in R_{\mathcal{L}}(x)\}_{x\in\mathcal{L}}$ and $\{w_x^2 \colon (x, w_x) \in R_{\mathcal{L}}(x)\}_{x\in\mathcal{L}}$

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Definition 2 (NIZK)

The *non interactive* PPT's (P, V) is a NIZK for $\mathcal{L} \in \mathrm{NP}$, if $\exists \ell \in$ poly s.t.

- **Completeness:** $\Pr_{c \leftarrow \{0,1\}^{\ell(|x|)}}[\mathsf{V}(x, c, \mathsf{P}(x, w(x), c)) = 1] \geq 2/3$, where $w(x) \in R_{\mathcal{L}}(x)$ for any $x \in \mathcal{L}$ (w is an arbitrary function)
- **Soundness:** $\Pr_{c \leftarrow \{0,1\}^{\ell(|x|)}}[\mathsf{V}(x, c, \mathsf{P}^*(x, c)) = 1] \leq 1/3$, for any P^* and $x \notin \mathcal{L}$
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Section 1

NIZK in HBM

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Let c^H be the “hidden" CRS:

- Prover sees c^H, and outputs a proof π and a set on indices $\mathcal{I}$
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We give a NIZK for HC - Directed Graph Hamiltonicity, in the HBM, and then transfer it into a NIZK in the standard model.

Implies a (standard model) NIZK for all NP

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Claim 3

Let T be a random $n^3 \times n^3$ Boolean matrix where each entry is 1 w.p n^{-5}. Hence, $\Pr[T \text{ is useful}] \in \Omega(n^{-3/2})$.

Proving Claim 3

- The expected one entries in T is $n^6 \cdot n^{-5} = n$ and by extended Chernoff bound, w.p. $\theta(1/\sqrt{n})$ T contains *exactly* n ones.

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- Hence, wp $\theta(1/\sqrt{n})$ the matrix T contains a permutation matrix and all its other entries are zero.
- A random permutation matrix forms a cycle wp $1/n$ (there are $n!$ permutation matrices and $(n-1)!$ of them form a cycle)

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Algorithm 4 (P)

Input: G and a cycle C in G. A CRS $T \in \{0,1\}_{n^3 \times n^3}$

1. If T not useful, set $\mathcal{I} = n^3 \times n^3$ (i.e., reveal all T) and $\phi = \perp$ Otherwise, let H be the (generalized) $n \times n$ sub matrix containing the hamiltonian cycle in T.
2. Set $\mathcal{I} = T \setminus H$ (i.e., , reveal the bits of T outside of H)
3. Choose $\phi \leftarrow \Pi_n$, s.t. C is mapped to the cycle in H
4. Add all the entries in H corresponding to non edges in G (with respect to ϕ) to $\mathcal{I}$
5. Output $\pi = (\mathcal{I}, \phi)$

NIZK for Hamiltonicity in HBM cont.

Algorithm 5 (V)

Input: a graph G, index set $\mathcal{I} \subseteq [n^3] \times [n^3]$, ordered set $\{T_i\}_{i\in\mathcal{I}}$ and a mapping ϕ

1. If all the bits of T are revealed and T is not useful, accept. Otherwise,
2. Verify that $\exists$ $n \times n$ submatrix $H \subseteq T$ with all entries in $T \setminus H$ are zeros.
3. Verify that $\phi \in \Pi_n$, and that all the entries of H not corresponding (according to ϕ) to edges of G are zeros

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Claim 6

The above protocol is a perfect NIZK for HC in the HBM, with perfect completeness and soundness error $1 - \Omega(n^{-3/2})$

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- Zero knowledge?

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- For useful T, the location of H is uniform in the real and simulated case.
- ϕ is a random element in Π_n is both cases
- Hence, the simulation is perfect

Section 2

From HBM to Standard NIZK

trapdoor permutations

Definition 8 (trapdoor permutations)

A triplet of PPT's (G, f, Inv) is called (enhanced) family of trapdoor permutation (TDP), if the following holds:

1. $G\colon \{0,1\}^n \mapsto \{0,1\}^n$ for every $n \in \mathbb{N}$.
2. $f_{pk} = f(pk, \cdot)$ is a permutation over $\{0,1\}^n$, for every $pk \in \{0,1\}^n$.
3. $\mathrm{Inv}(sk, \cdot) \equiv f^{-1}_{G(sk)}$ for every $sk \in \{0,1\}^n$
4. For any PPT A, $\Pr_{x \leftarrow \{0,1\}^n, sk \leftarrow \{0,1\}^n, x = G(sk)}[\mathsf{A}(pk, x) = f^{-1}_{pk}(x)] = \mathrm{neg}(n)$

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- For our purposes, somewhat less restrictive requirements will do

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Factoring is easy $\implies$ RSA is easy.

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  In particular, $(x^e)^d \equiv x \bmod n$, for every $x \in \mathbb{Z}_n^*$, where $d \equiv e^{-1} \bmod \phi(n)$

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- $G(p, q)$ sets $pk = (n = pq, e)$ for some $e \in \mathbb{Z}_{\phi(n)}^*$, and $sk = (n, d \equiv e^{-1} \bmod \phi(n))$
- $f(pk, x) = x^e \bmod n$
- $\mathrm{Inv}(sk, x) = x^d \bmod n$

Factoring is easy $\implies$ RSA is easy. Other direction?

The transformation

Let $(\mathsf{P}_H, \mathsf{V}_H)$ be a HBM NIZK for $\mathcal{L}$, and let $\ell(n)$ be the length of the CRS used for $x \in \{0,1\}^n$.
Let (G, f, Inv) be a TDP and let b be an hardcore bit for f.

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Let (G, f, Inv) be a TDP and let b be an hardcore bit for f.
We construct a NIZK (P, V) for $\mathcal{L}$, with the same completeness and “not too large" soundness error.

The protocol

Algorithm 10 (P)

Input: $x \in \mathcal{L}$, $w \in R_{\mathcal{L}}(x)$ and CRS $c = (c_1, \ldots, c_\ell) \in \{0,1\}^{n\ell}$, where $n = |x|$ and $\ell = \ell(n)$.

1. Choose $sk \leftarrow U_n$, set $pk = G(sk)$ and compute $c^H = (b(z_1 = f_{pk}^{-1}(c_1)), \ldots, b(z_{\ell(n)} = f_{pk}^{-1}(c_\ell)))$
2. Let $(\pi_H, \mathcal{I}) \leftarrow \mathrm{P}_H(x, w, c^H)$ and output $(\pi_H, \mathcal{I}, pk, \{z_i\}_{i \in \mathcal{I}})$

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Algorithm 11 (V)

Input: $x \in \mathcal{L}$, CRS $c = (c_1, \ldots, c_\ell) \in \{0,1\}^{np}$, and $(\pi_H, \mathcal{I}, pk, \{z_i\}_{i \in \mathcal{I}})$, where $n = |x|$ and $\ell = \ell(n)$.

1. Verify that $pk \in \{0,1\}^n$ and that $f_{pk}(z_i) = c_i$ for every $i \in \mathcal{I}$
2. Return $\mathsf{V}_H(x, \pi_H, \mathcal{I}, c^H)$, where $c_i^H = b(z_i)$ for every $i \in \mathcal{I}$.

Claim 12

Assuming that $(\mathsf{P}_H, \mathsf{V}_H)$ is a NIZK for $\mathcal{L}$ in the HBM with soundness error $2^{-n} \cdot \alpha$, then (P, V) is a NIZK for $\mathcal{L}$ with the same completeness, and soundness error α.

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For every $pk \in \{0,1\}^n$: $\left(b(f_{pk}^{-1}(c_1)), \ldots, b(f_{pk}^{-1}(c_\ell))\right)_{c \leftarrow \{0,1\}^{np}}$ is uniformly distributed in $\{0,1\}^\ell$.

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- Zero knowledge:?

Proving zero knowledge

Algorithm 13 (S)

Input: $x \in \{0,1\}^n$ of length n.

- Let $(\pi_H, \mathcal{I}, c^H) = \mathsf{S}_H(x)$, where S_H is the simulator of $(\mathsf{P}_H, \mathsf{V}_H)$
- Output $(c, (\pi_H, \mathcal{I}, pk, \{z_i\}_{i\in\mathcal{I}}))$, where
  - $pk \leftarrow G(U_n)$
  - Each z_i is chosen at random in $\{0,1\}^n$ such that $b(z_i) = c_i^H$
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- Exists efficient M s.t. $M(\mathsf{S}_H(x)) \equiv \mathsf{S}(x)$ and $M(\mathsf{P}_H(x, w_x)) \approx_c \mathsf{P}(x, w_x)$

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- Distinguishing $\mathsf{P}(x, w_x)$ from $\mathsf{S}(x)$ is hard

Section 3

Adaptive NIZK

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- **Completeness:** $\forall f\colon \{0,1\}^{\ell(n)} \mapsto \mathcal{L} \cap \{0,1\}^n$: $\Pr_{c \leftarrow \{0,1\}^{\ell(n)}}[\mathsf{V}(f(c), c, \mathsf{P}(f(c), w(f(c)), c)) = 1] \geq 2/3$

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$$\{(f(c), c, \mathsf{P}(f(c), w(f(c)), c \leftarrow \{0,1\}^{\ell(n)})\}_{n \in \mathbb{N}} \approx_c \{\mathsf{S}^f(n)\}_{n \in \mathbb{N}}.$$

where $\mathsf{S}^f(n)$ is the output of the following process

1. $(c, s) \leftarrow \mathsf{S}_1(1^n)$
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Theorem 14

Assume TDP exist, then every NP *language has an adaptive* NIZK *with perfect completeness and negligible soundness error.*

In the following, when saying adaptive NIZK, we mean negligible completeness and soundness error.

Section 4

Simulation Sound NIZK

Simulation Soundness

A NIZK system (P, V) for $\mathcal{L}$ has *(one-time) simulation soundness*, if $\exists$ a pair of PPT's $\mathsf{S} = (\mathsf{S}_1, \mathsf{S}_2)$ satisfying the ZK property of P with respect to $\mathcal{L}$, such that the following holds $\forall$ pair of PPT's $(\mathsf{P}_1^*, \mathsf{P}_2^*)$: let

Experiment 15 ($\mathsf{Exp}^n_{\mathsf{V},\mathsf{S},\mathsf{P}^*}$)

1. $(c, s) \leftarrow \mathsf{S}_1(1^n)$
2. $(x, p) \leftarrow \mathsf{P}_1^*(1^n, c)$
3. $\pi \leftarrow \mathsf{S}_2(x, c, s)$
4. $(x', \pi') \leftarrow \mathsf{P}_2^*(p, \pi)$
5. Output (r, x, π, x', π')

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We require $\Pr[(r, x, \pi, x', \pi') \leftarrow \mathsf{Exp}^n_{\mathsf{V},\mathsf{S},\mathsf{P}^*} : x' \notin \mathcal{L} \wedge \mathsf{V}(x', \pi', c) = 1 \wedge (x', \pi') \neq (x, \pi)] = \mathsf{neg}(n)$.

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- (P, V) might be adaptive or non-adaptive
- Adaptive NIZK guarantees weak type of simulation soundness
- Does the adaptive NIZK we seen in class have simulation soundness?

Construction

We present a simulation sound NIZK (P, V) for $\mathcal{L} \in \mathrm{NP}$

Ingredients:

1. Strong signature scheme $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$

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   - Pseudorandom range: for some $\ell \in$ poly $\{\mathsf{Com}(s, r \leftarrow \{0,1\}^{\ell(|s|)}\}_{s \in \{0,1\}^*} \approx_c \{u \leftarrow \{0,1\}^{\ell(|s|)}\}_{s \in \{0,1\}^*}$

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   *adaptive WI suffices

Algorithm 16 (P)

Input: $x \in \mathcal{L}$ and $w \in R_{\mathcal{L}}(x)$, and CRS $r = (r_1, r_2)$

1. $(sk, vk) \leftarrow \mathrm{Gen}(1^{|x|})$
2. $\pi_A \leftarrow \mathrm{P}_A((x, r_1, vk), w, r_2)$
3. $\sigma \leftarrow \mathrm{Sign}_{sk}(x, \pi_A)$
4. Output $\pi = (vk, \pi_A, \sigma)$

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Algorithm 17 (V)

Input: $x \in \{0,1\}^*$, $\pi = (vk, \pi_A, \sigma)$ and a CRS $r = (r_1, r_2)$
Verify that $\mathrm{Vrfy}_{vk}((x, \pi), \sigma) = 1$ and $\mathrm{V}_A((x, r_1, vk), r_2, \pi_A) = 1$

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Claim 18

The proof system (P, V) is an adaptive NIZK for $\mathcal{L}$ with one-time simulation soundness.

Proving Claim ??

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    2. Output $(r = (r_1, r_2), s = (z, sk, vk))$, where r_2 is chosen uniformly at random
  - $S_2(x, r, s = (z, sk, vk))$:
    1. let $\pi_A \leftarrow P_A((x, r_1, vk), z, r_2)$
    2. $\sigma \leftarrow \mathsf{Sign}_{sk}(x, \pi_A)$
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  Proof follows by the adaptive WI of $(\mathsf{P}_A, \mathsf{V}_A)$ and the pseudorandomness of Com
  - **Adaptive soundness:** Implicit in the proof of simulation soundness, given below

Proving simulation soundness

Let $\mathsf{P}^* = (\mathsf{P}_1^*, \mathsf{P}_2^*)$ be a pair of PPT's attacking the simulation soundness of (V, S) with respect to $\mathcal{L}$, and let $r = (r_1, r_2)$, x , π, x' and $\pi' = (vk', \pi'_A, \sigma')$ be the values generated by a random execution of $\mathrm{Exp}^n_{\mathsf{V},\mathsf{S},\mathsf{P}^*}$.

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Assuming $\mathsf{Vrfy}_{vk'}((x', \pi'_A), \sigma') = 1$, $x' \notin \mathcal{L}$ and $(x', \pi') \neq (x, \pi)$, then with save but negligible probability:

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Since r_2 was chosen at random by S_1, the adaptive soundness of (P_A, V_A) yields that $\Pr[V_A(x'_A, r_2, \pi'_A) = 1] = \text{neg}(n)$.

Part II

Proof of Knowledge

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Let (P, V) be an interactive proof $\mathcal{L} \in \mathrm{NP}$. A probabilistic machine E is a knowledge extractor for (P, V) and $R_{\mathcal{L}}$ with error $\eta \colon \mathbb{N} \mapsto \mathbb{R}$, if $\exists t \in$ poly s.t. $\forall x \in \mathcal{L}$ and deterministic algorithm P^*, $\mathsf{E}^{\mathsf{P}^*}(x)$ runs in expected time bounded by $\frac{t(|x|)}{\delta(x)-\eta(|x|)}$ and outputs $w \in R_{\mathcal{L}}(x)$, where $\delta(x) = \Pr[(\mathsf{P}^*, \mathsf{V})(x) = 1]$.

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- Relation to ZK

Examples

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The ZK proof we've seen in class for GI, has a knowledge extractor with error $\frac{1}{2}$.

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